Anik E2

A case study in ground-based attitude control recovery methods

In 1994, Anik E2 lost all attitude control when its momentum wheels became inoperative. An innovative ground-based attitude determination and control methodology had to be developed to recover the satellite.

AE403: Attitude Determination and Control
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Introduction

In 1994, Telesat Canada's Anik E1 and Anik E2 satellites both experienced an attitude control failure. While Anik E1 was recovered under its own power, Anik E2 began tumbling uncontrollably. The satellite was eventually recovered using a unique ground-based determination and control system. This report, written for the AE403 Attitude Determination and Control course, investigates and discusses the incident and its solution, both in the context of the era, and as it applies to modern satellites.

Background

Telesat and the History of the Anik Project

Originally created as a crown corporation of Canada by an act of Parliament in 1969, (1) Telesat was created to be the owner and operator of Canada's domestic satellite communications system. Starting with the three single band Anik A satellites (launched 1972 through 1975), Telesat provided twelve RF channels in the C-band range (2) across Canada, allowing television access to the entire country, including the northern territories. The Anik A satellites were the world's first national domestic satellites, although not the world's first communication satellites. (3) They were followed by the 1978 launch of the Anik B series, a dual band system providing channels at both the C and Ku ranges. The Anik A series was retired from 1982-1984, around the same time the C and D series were launched. As a change from the Anik B series philosophy, the Anik C series was dedicated to the Ku band, while the Anik D series was dedicated to the C band. (2) At the time, the dedication of each satellite to a certain band allowed for more and better quality channel transmission.

In a return to the Anik B concept, the Anik E series was designed to be a dual-band satellite system to replace the Anik C and D series satellites and provide service through the 1990s. At a significant manufacturing and operating cost savings but with the risk of reducing system redundancy, Telesat chose to reduce the constellation of three Cs and two Ds down to a pair of E satellites. (2) Since both the C and D series would be decommissioned in the same timeframe, each Anik E satellite needed to be capable of providing coverage of both channels over the whole country.

The Anik E series was launched in 1991; Anik E2 in April, and Anik E1 in September. (4) Shortly after launch, Anik E2 suffered an antenna deployment problem. While this is not the incident in question, it did give the operations team valuable experience in troubleshooting the satellites. (1)

The Anik E Satellites

While Telesat was a strong satellite operator, itdid not build its own hardware. The Anik E series satellites were contracted to Spar Aerospace (creators of the Canadarm) who, in turn, sub-contracted out the bus design to RCA (at the time of the design a subsidiary of General Electric, but during the incident, owned by Martin Marietta). RCA provided itsstandard Astro 5000 model, which was designed for operation in geostationary orbit. (5)

The Anik E satellites were critical for Canadian telecommunication. During the 1990s the E series "carried most Canadian broadcasting signals, including 50 television and 100 radio channels" (5). The satellites had a ten-year design lifetime for the payload, and a twelve year design lifetime on the service bus. The extra two-year life on the non-payload equipment was designed so that the two satellites could be launched within a year of each other (to prevent any launch system failures) while having the first satellite wait for the second before beginning its communication mission. (2) The rate at which the Anik C and D constellations were expected to be decommissioned meant that should the first or second launch fail, a single Anik E satellite could supplement the remaining Anik C and D systems and there would be no break in service until a replacement Anik E could be launched.

The satellites had a launch mass of 2930 kg $(\approx 6500\ lb)$ (5). The satellites had twenty-two thrusters (6), sixteen of which used catalytic hydrazine as part of an attitude reaction control system. (1) Four were electro-thermal hydrazine for north-south stationkeeping, and the remaining two were bi-propellant apogee kick motors. (5) As is common with communication satellites, the Anik E series was geostationary, positioned at 107.5 W (E1) and 110.5 W (E2). (5) The primary payload was a pair of communication dishes. The satellites were capable of providing 24 C-band and 16 Ku-band channels, totalling a radiofrequency power of 800W. The full solar array, when deployed, was 33m^2, intended to produce 3.2kW of power at end of life. During eclipse, four Nickel-Hydrogen batteries provided 50 A-Hr of power each. (5) Both payloads had near-full coverage of Canada, with the C-band covering all but the furthest North, and the Ku band covering all but the territories. The system could also target most American cities, depending on Canadian usage (which had priority). (2) The satellite also had an HDTV payload, and direct-to-home capabilities. (5) As communication payloads generate significant heat, a thermal control system was implemented which tied the payloads directly to radiators via heat pipes. During normal operation, this kept the satellite well within acceptable temperature ranges. The system was also protected 100% from eclipse times, using four 50 Ampere-Hour batteries.

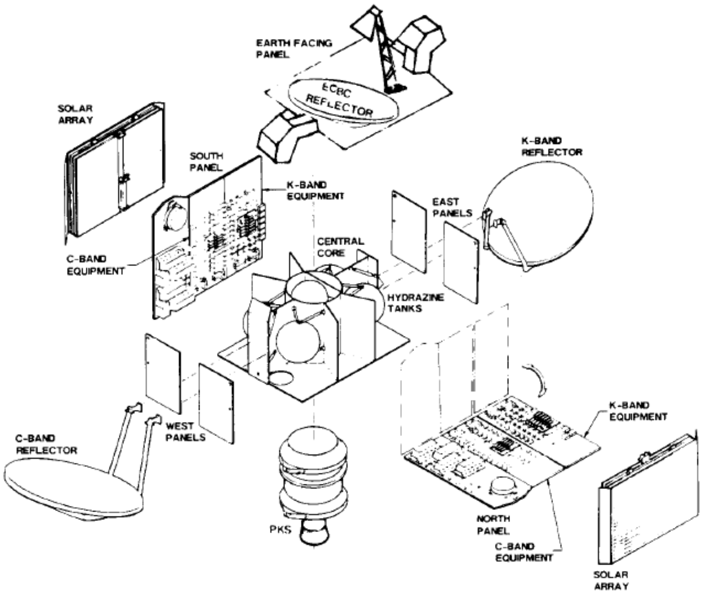

Figure 1: Anik E Hardware Configuration (2)

Attitude Control System

The satellites were 3-axis stabilized using a biased momentum system. Each satellite had a primary and redundant momentum wheel, all capable of a 2.5° roll pivot. (7) In addition to the reaction control system thrusters (primarily intended for momentum dumping and station keeping), magnetic torquers were available in the roll and yaw axes. Attitude error was determined using Earth Sensors in the pitch and roll directions. Additionally, rate gyros existed to sense angular rate and position in all three axes. There was no method for absolute measurement of the yaw axis (1); however, such a device was not necessary, since the assumed momentum of the wheels would interchange between the roll and yaw axes through a quarter orbit. Pitch errors were corrected by exchanging momentum between the momentum wheel assembly and the body, while roll and yaw was corrected using the magnetic torquers (7). Two on-board attitude processor units were present, and these were capable of autonomously station keeping and maintaining the attitude. These units were not ground programmable; however, all attitude determination data and direct control over all thrusters, wheels, and torquers was individually ground commandable. This design feature was required after an attitude control incident had occurred on an Anik B satellite. (1)

Incident Description

Anik E1

On January 20th, 1994 Anik E1 lost attitude control, and at approximately 12:30pm, began to spin up about the pitch axis. It was determined that the primary momentum wheel was malfunctioning. The unit was requesting full speed, while the actual wheel was slowing down. The redundant unit was activated and attitude was restored. Shortly thereafter, the redundant wheel suffered a failure. The position sensor on the wheel failed, causing the pivot to its hard stop. Fortunately, the problem was corrected by resetting the circuits, and the pivot was able to be re-levelled. By 8:00pm, full pointing control was restored, and Anik E1 continued to operate normally. (1)

Anik E2

At approximately 9:30pm, the same day, Anik E2 experienced a similar failure. Unfortunately, unlike Anik E1, when the redundant unit was activated, it immediately failed in the same manner as both the E1 and E2 primary wheels (wheel not responding to driven commands and slowing down). Unlike Anik E1, Anik E2 was not recoverable through the intended backup system. (1)

It should be noted that by 1994, the Anik E constellation had been in orbit for three years, and had taken over as the primary satellite communication provider for Telesat. One of the Anik D satellites had already been retired (5), and the remaining Anik D and Anik C satellites were apparently unavailable or re-tasked. This has not been confirmed for this document; however, reports were clear that the loss of Anik E2 represented a loss of 50% of Telesat (and therefore Canada's) telecommunication capability (1) (7) (4).

Immediately following the event, the situation for Anik E2 was far from desirable. The solar arrays on the spinning satellite were no longer sun-pointing; and only a quarter of their nominal output was being produced. The primary communications payload had been shutdown to conserve power, however, without the extra heat produced by its operation, the satellite was rapidly cooling, and some components were approaching thermal survival limits. To add to the issues, the nutation was increasing by six degrees per day on the satellite's spin. Within a couple of weeks the satellite would fall over to spin about the major axis, which would have been very difficult to reverse. (1)

Telesat was able to move much of the traffic from E2 onto E1, and they also bought time on other satellites for the remainder of their major clients; however, not all traffic was recovered. Between losing the use of a $300 million satellite, and having to purchase traffic on other networks, Telesat was operating at a loss, and was looking at bankruptcy should the satellite be unrecoverable. (7)

Probable Cause

The likely cause of the momentum wheel failures is attributed a electrostatic discharge event within both satellites. (8) Based on information available from the GOES satellite constellation, and made available from the National Oceanic and Atmospheric Administration, there was increased solar activity that started on the 13th and ended sometime around the 21st. (9) Raised solar activity can always be problematic for satellites; however they are typically shielded from radiation. The solar activity led to an integrated circuit failure on the control circuitry for three of the four momentum wheels across the two satellites[1]. The failed devices fed back full speed, and thus no speed increases were ever demanded from their motors. (7) A flaw in the momentum wheel design evidently made them more susceptible to radiation-related failures. The wheels themselves were located externally to the main satellite chassis; however, the electronic harness carried the short into the satellite past its faraday cage, frying the wheel control circuits.

The Solution

After some deliberation, it was determined that a solution was possible. Two phases were necessary: within days of the incident, the satellite had to be placed in a stable 'hold' position that would not significantly impact the lifetime of the satellite, and a longer-term solution was necessary to regain useful, automated attitude pointing. A deadline of August 1st was set for the full resumption of Anik E2 service, chosen for fiscal reasons. (1) The initially estimated cost of the recovery effort was $3 million, a reasonable price considering the $300 million cost of the satellite. (8)

The satellite was now a zero momentum satellite, meaning all the existing control logic made assumptions that were no longer true. (1) For zero momentum systems, rate feedback is typically used to create stable attitude control loops. While Anik E did have rate gyros which were capable of providing these rates, these gyros were designed for intermittent operation only, and did not have the lifetime expectancy to be run continuously. (10) The earth sensors were still operating normally (1), and the onboard attitude control computers were also fully operational, but not reprogrammable. (10) This meant that some form of ground-based attitude control solution was needed that could feed control requests to the thrusters and magnetic torquers (recall that these are ground commandable if

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[1] During a discussion with Mr. Burlton, he mentioned that the reason the 4th momentum wheel was not affected was believed to be related to an assembly and integration incident. While still on the ground, the Anik E1 redundant wheel was removed and reworked. Aside from this one conversation, this could not be confirmed, nor was the nature of this work determined. I have contacted people formerly from Spar and from the CSA who worked on the ground campaign, and they believe that such a rework occurred at Astro before delivery. I lost the trail at that point, and thus the reason for the 4th wheel's rework (what happened to it and why) remains a mystery.

necessary). The aspects of the existing control logic pertaining to station keeping were still valid, as they did not depend on the momentum wheels, but for attitude control, the on-board processors would need to be circumvented.

To resume full Anik E2 service with minimal impact to lifetime, a target-pointing budget was developed. This is presented in Table 1.

Table 1: Target Pointing Budget

Parameter	Target
Yaw Axis Accuracy	$\pm 1°$
Roll Axis Accuracy	$\pm 0.25°$
Pitch Axis Accuracy	$\pm 0.25°$
Additional Fuel Consumption	10 lb per year

The Short Term Solution – Yaw Spin

Using a series of thruster burns, the satellite was put into a yaw spin. This manoeuvre was performed three weeks after the initial failure. The yaw axis would be oriented towards the sun, allowing the solar arrays to gather energy and keep the satellite warm and powered. A 30° offset between the yaw axis and the sun vector was selected, primarily to protect the earth sensors. (1)

As the solar panels were individually commandable (7), they were offset from each other by six degrees. This produced a solar torque which was sufficient to precessthe satellite about the yaw axis towards the sun at one degree per day. Such a precession meant that the satellite was in a stable position, able to maintain power and attitude stability while it was waiting for the larger solution. The primary control required was the normal amounts of north-south stationkeeping. Additionally, attitude corrections were required every 10 days to maintain the yaw axis in the plane of the orbit and ensure the spin rate was not retarding. (1)

Ground Looped Attitude Control System (GLACS)

As previously mentioned, in a momentum free system, feedback is necessary in all three axes. (10) The rate gyros were not a viable option, and the existing earth sensors were only designed to measure in the roll and pitch axes. (1) A new system was necessary to determine the yaw attitude, and as the on-board attitude control processor was not reprogrammable, this solution had to be located on the ground.

The solution was found within the communication payload itself. All communication signals on the C and Ku band were normally polarized either horizontal or vertical. Two channels on the Ku band were diverted from communication usage to be used for the attitude control system. These channels were polarized at 45° from the normal signals. By measuring the relative polarization and amplitude of the two signals, the nominal vector of their orthogonal component could be calculated and thus the yaw angle determined on the ground in real-time. (1) To ensure the system was closed-loop control, the new determination and control logic had to be automated, and located at the ground stations themselves. Two ground stations were upgraded with the system for redundancy, on opposite sides of the country (Alberta and Ontario.) Since this system would be operating in constantly, a redundant station was necessary to mitigate any weather effects or ground station problems that would constitute a disruption of the control loop. Each ground station had two dishes for receiving the signals, a primary control computer and a backup. While GLACS was only required to control Anik E2, the system had duplicate equipment installed at the same time, to prepare for any future need to also switch E1 to this system. (7)

This used the ground-calculated yaw, and received telemetry data from the earth sensors to calculate the required actuation to maintain attitude control. The satellite's original on-board station keeping logic was unaffected by the new system, so long as the attitude was maintained. (10)

To summarize the new attitude control scheme:

1. Onboard earth sensors detect the roll and pitch attitude
2. A ground control loop involving the polarity angle of two signals is used to calculate the yaw.
3. An automated ground computer calculates the necessary actuation, and sends up the instructions directly to the instruments.
4. Magnetic torquers are used in the roll and yaw axes.
5. Thrusters are used in all three axes (and especially the pitch axis).
6. The on-board computer continues to handle automated stationkeeping.

Control Modes

The system had three operational modes. The first is the stationkeeping mode, which remains unchanged from the original design, and depends exclusively on the satellite's on-board equipment and logic to maintain its orbit. The ground control logic had two remaining modes: normal and acquisition. The acquisition mode was capable of recovering from large attitude errors, but at a higher fuel cost. The normal mode provided a more efficient use of fuel, as it used thrusters for pitch control only, and depended on the magnetometers for roll and yaw control. The normal mode uses the ground-based RF data to determine yaw, whereas in acquisition mode, the on-board gyros are turned on and used.(10) As acquisition mode was not intended to be needed regularly; its use would not tax the life of the gyros.

The attitude errors calculated by the ground equipment were then fed into a new proportional-integral-controller, which produced the required torques. This, in turn, was fed into actuator command processing logic, which determined the required thrusters and magnetometer usage, and uplinked this to the satellite. Reference (10) goes into substantial detail on the control logic, including block diagrams and system performance graphs.

System Performance

Recall Table 1, above, which delineates the required pointing accuracy to maintain full service of Anik E2. The experienced performance of the GLACS far surpassed these goals. Table 2, below, provides a comparison. Additionally, during the planning phases of this recovery scheme, the expected lifetime of Anik E2 post-recovery was initially "eight or nine years instead of 10 years anticipated before the mishap" (8). Later, after the initial success was confirmed, the lifetime reduction was expected to be only a 1 year loss (i.e. nine years). (6) Ultimately, Anik E1 and E2 were retired in 2005, exceeding their predicted lifetime. (11)

Table 2: Actual Performance Comparison (7), (10)

Parameter	Target	Expected	Actual
Yaw Axis Accuracy	±1°	±0.25°	±0.1°
Roll Axis Accuracy	±0.25°	±0.05°	±0.05°
Pitch Axis Accuracy	±0.25°	±0.25°	±0.20°

Lessons Learned

The Anik E2 recovery was unique in many ways. It was the first time that a satellite using momentum wheels was recovered and used an alternative control system for permanent control. (8) While ground-loop attitude control had been previously demonstrated, Anik E2 also proved the viability of a remote-sensed attitude determination method, and did so with a system latency short enough for real-time actuation. The entire system would not have been achievable had the actuators not been ground-commandable (8), a lesson they learned from a previous Anik B failure. This is a point that should be encouraged on all satellites; complete ground-override allows for better adaptability to unpredictable failures. The Anik E attitude control processor itself was not re-programmable, but modern technology has made such features cheap and easy to implement. Had such been the case on the Anik Es, the ground stations would have been necessary only for the yaw determination, and not for all the control logic.

It should be noted, however, that the communications-based attitude determination system would not be applicable to all satellites. In a non-geostationary orbit, this system would be expensive as ground stations would be required around the world. The saving grace of this design was the willingness of Telesat to lose two communication channels in exchange for an operating statellite: such options are not available on most satellites, as they will not have accurately reconfigurable radiofrequency signals to spare for adjustment. Alternatively, rate gyros could be used whenever out of range; however, this would have decreased the lifetime of the satellite, and likely have had propagation errors.

Solar radiation, especially sudden peaks, are very difficult to predict. While Anik E1 and E2 experienced the standard ground testing campaign, evidently the levels of radiation testing were not sufficient for a true ‘worst case’ scenario. The reaction wheels outside the satellite were evidently not sufficiently shielded, but additionally the satellite’s grounding scheme did not protect it from this fault. Anytime a harness passes through a satellite’s faraday cage (or whatever other external-charge prevention method is used) it should be given additional scrutiny during the ground testing campaign. Typically, redundancy is used to prevent this sort of failure, yet both the primary and the redundant wheel failed in Anik E2. Redundancy solutions are better suited to failures due to fatigue or lifetime concerns. Only through more extensive testing could the wheel failure have been prevented. There will never be a sure-fire radiation test, but future satellites which have long mission lifetimes should be subjected to a radiation intensity that is a factor of safety larger than the currently recorded strongest events. Such a test could be expensive, but on a $300+ million satellite, it would be merited to avoid the kind of incidents experienced by the Anik E satellites.

Conclusion

Anik E2 resumed service on August 1st, 1994, about six months after the solar flare. What could have been a financial disaster, turned into a technical demonstration success, proving a methodology for ground-determined attitude on geostationary communication satellites.

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